

XMM observations of BAL Quasars with polar outflows

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ABSTRACT

We have selected a sample of broad absorption line (BAL) quasars which show significant radio variations, indicating the presence of polar BAL outflows. We obtained snapshot XMM observations of four polar BAL QSOs, to check whether strong X-ray absorption, one of the most prominent characteristics of most BAL QSOs, also exist in polar outflows. Two of the sources are detected in X-ray. Spectral fittings show that they are X-ray normal with no intrinsic X-ray absorption, suggesting the X-ray shielding gas might be absent in polar BAL outflows. Comparing to non-BAL QSOs, one of two X-ray nondetected sources remains consistent with X-ray normal, while the other one, which is an iron low-ionization BAL (FeLoBAL), shows an X-ray weakness factor of > 19 , suggesting strong intrinsic X-ray absorption. Alternative explanations to the nondetection of strong X-ray absorption in the two X-ray detected sources are 1) the absorption is more complex than a simple neutral absorber, such as partial covering absorption or ionized absorption; 2) there might be significant jet contribution to the detected X-ray emission. Current data is insufficient to test these possibilities, and further observations are required to understand the X-ray nature of polar BAL outflows.

Subject headings: quasars: general — quasars: absorption lines — radiation: radio continuum

1. Introduction

Broad UV absorption troughs in resonant lines are seen in about 10-20 % optically selected QSOs (Hewett & Foltz 2003; Reichard et al. 2003a). The broad absorption lines (BALs) are found blueshifted up to 0.1c to the corresponding emission lines, suggesting

that they are formed in a partially ionized wind, outflowing from the quasar. The covering factor of the BAL Region (BALR) was found to be $< 20\%$ based on the observed flux ratios of the emission to absorption line (Hamann, Korista & Morris 1993). It's found that the properties of UV continuum and emission lines of BAL QSOs and non-BAL QSOs are similar (Weymann et al. 1991; Reichard et al. 2003b). Observations also show that the de-absorbed X-ray emission of BAL QSOs is consistent with non-BAL QSOs (e.g. Green et al. 2001). Recently, Gallagher et al. (2007) found mid-infrared properties of BAL QSOs agree with those of non-BAL quasars. It is now widely accepted that BALR covers only a small fraction of sky, and most (if not all) BAL QSOs represent a special line of sight toward a QSO nucleus (Weymann et al. 1991).

The popular models suggest that BAL quasars are normal quasars viewed edge-on, skimming the torus and through a wind. For instance, Murray et al. (1995) suggested that BALs present themselves when the line of sight passes through the accretion disk wind nearly at the equatorial plane. Elvis (2000) appealed to a funnel-shaped thin shell outflow that arises from the accretion disk to explain various observational properties of quasars. Both models require a rather large incline angle of $i \sim 60^\circ$ for BAL quasars. However, recent numerical work indicates that it is also plausible to launch bipolar outflows from the inner regions of a thin disk (e.g. Punsly 1999; Proga & Kallman 2004). There are growing observational evidence indicating the existence of polar BAL outflows (e.g. Brotherton, De Breuck & Schaefer 2006; Punsly & Lipari 2005; Ghosh & Punsly 2007; Zhou et al. 2006; Becker et al. 2000; Barvainis & Lonsdale 1997; Jiang & Wang 2003).

BAL QSOs are found to be X-ray weak following the work of Green & Mathur (1996, but see Ghosh & Punsly 2008 for the discovery of three soft X-ray loud BAL QSOs without intrinsic X-ray absorption). For radio quiet BALs, there are strong evidence showing that the weakness in X-rays is not intrinsic but due to strong X-ray absorption, with the hydrogen column density of a few 10^{22} to $> 10^{24} \text{ cm}^{-2}$ (Wang et al. 1999; Mathur et al. 2000; Gallagher et al. 2002, 2006; Grupe, Mathur & Elvis 2003). Although UV and X-ray absorption are clearly linked, the X-ray column density detected in the X-ray band is much higher. A possible model for the X-ray absorber is the "shielding gas" postulated by Murray et al. (1995) and it could be generated naturally in the simulations of Proga, Stone & Kallman (2000). Radio loud BALs appear similar in X-ray. Brotherton et al. (2005) found that similar to radio-quiet BALs, 5 radio loud BALs are also weaker in X-ray by factors of 40 or more compared to normal unabsorbed radio loud quasars. However, the hardness ratios of these radio-loud BALs are rather soft, inconsistent with simple neutral absorption. The unabsorbed X-ray emission might be associated with a radio jet, a partial-covering absorber, or scattered emission which is not absorbed. Similarly, Miller et al. (2006) found variable and complex soft X-ray absorption (probably a partial-covering absorber) in radio-loud BAL

Quasar PG 1004+130 (also see Schaefer et al. 2006 for X-ray data of radio-loud BAL Quasar FIRST J101614.3+520916).

In a previous paper, we have selected a sample of BAL QSOs from the SDSS (the Sloan Digital Sky Survey, York et al. 2000) Quasar Catalog with significant variations in radio band (Zhou et al. 2006). The large amplitudes of the variations imply brightness temperatures much higher than the inverse Compton limits (10^{12} K), suggesting the presence of relativistic jets beaming toward the observer. As revealed by both theoretical models and numerical simulations (e.g. Blandford & Znajek 1977; McKinney & Gammie 2004), the relativistic jet is believed to be perpendicular to the inner accretion disk. Also note that VLBI observations have shown the inner accretion disk (within 1 pc scale) in NGC 1068 is aligned perpendicular to the radio jet (Gallimore, Baum & O’Dea 2004). This implies that the BAL outflows in these quasars are almost orthogonal to the accretion disc. We propose snapshot XMM observations to check whether strong X-ray absorption, one of the most prominent characteristics of most BAL QSOs, also exist in the polar outflows, and to check whether face-on BAL QSOs are otherwise X-ray normal. In this letter we present XMM observations on four of the BAL QSOs with polar outflows. Throughout the paper, we assume a cosmology with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.3$, and $\Omega_\Lambda = 0.7$.

2. Sample selection, Observations and Data analysis

In the previous paper (Zhou et al. 2006), we have selected a sample of 8 BAL QSOs with polar outflows from SDSS DR3. XMM exposures on randomly selected four sources were obtained to study their X-ray properties. We note that Ghosh & Punsly (2007) applied similar selection to SDSS DR5, and corrected one error in our calculation of the low limit of the observed radio brightness temperature (Zhou et al. 2006). We revised our calculations and found three BAL QSOs with XMM exposures have observed brightness temperature (T_b) $\gtrsim 10^{12.7}$ K, well in excess of the inverse Compton limit, while the rest one, SDSS J210757-062010 has $T_b \gtrsim 10^{12}$ K. We note that however, the inverse Compton limit is a very conservative upper limit, which requires the radiating plasma to be very far out of equipartition (see Kellermann & Pauliny-Toth 1969), while the equipartition brightness temperature is $\sim 5 \times 10^{10}$ K (Readhead 1994). Homan et al. (2006) have measured the intrinsic T_b of the parsec-scale jet cores of AGNs and found intrinsic T_b of $\sim 2 \times 10^{11}$ K in their maximum brightness states. Based on these facts, we conclude that it’s still safe to consider all the four sources as polar BALs.

In table 1 we present the observational log for the *XMM-Newton* exposures on four BAL QSOs. During the exposures the EPIC-PN, MOS1 and MOS2 cameras were operated in Full

Frame mode and the thin filter was utilized. The Observation Data Files were processed to produce calibrated lists using the XMM-Newton Science Analysis System (SAS 7.0.0). Bad pixels were removed and EPIC response matrices were generated using the SAS tasks ARFGEN and RMFGEN. Time intervals of high background flaring were eliminated by examining the light curves of photons above 10 keV. The total good exposure times for all observations were listed in Table 1.

Two of the sources (SDSS J145926+493136 and SDSS J210757-062010) were not detected by any of the cameras (see Figure 1). For each source we extracted the X-ray photons from a circular region with a radius responding to the half energy width (HEW) of the PSFs¹. After subtracting the local background and applying aperture corrections, we calculate 1σ upper limit of 2.0 – 10.0 keV observed fluxes by assuming a power-law with photon index of 1.9 (see Table 1).

The rest two sources (SDSS J153703+533219 and SDSS J081102+500724) were detected by PN, MOS1 and MOS2 (see Fig. 2). We extract the source spectrum for each source from a 24'' circle, centered at the nominal source position. The blank field background spectra were extracted from nearby circular region with radius of 40'' free of other sources in the same CCD chip. Single and double events were selected for the PN detector, and single-quadruple events were selected for the MOS. We obtained 201.6 ± 20.8 net counts (PN) in 0.5 – 10 keV band for SDSS J153703+533219 and 174 ± 17.8 for SDSS J081102+500724, while the expected background level are 98.4 ± 5.9 and 63 ± 3.9 respectively. The resulting spectral files were grouped with at least one count per bin and C statistic (Cash 1979) was adopted for minimization. The responses of MOS1 and MOS2 cameras are nearly the same, thus we combined their spectra to increase signal-to-noise ratio (S/N). We fitted the 0.3 – 10.0 keV band spectra of PN and MOS simultaneously (Figure 2).

Our primary model is a power-law with intrinsic neutral absorption. The Galactic absorption was also accounted. We find that intrinsic absorption is statistically not required in either SDSS J153703+533219 or SDSS J081102+500724. The fitting results are listed in Table 1. Note all the statistical errors quoted in this paper are for 90% confidence, one interesting parameter. The spectra and the data to model ratios are presented in Fig. 2.

We noticed the very flat X-ray spectrum in SDSS J153703+533219 ($\Gamma = 1.31^{+0.20}_{-0.09}$), which could probably be due to more complex absorption. We thus applied a partial covering fraction absorption model instead, and obtained $\Gamma = 1.77^{+0.30}_{-0.36}$, $N_H = 12.9^{+5.8}_{-8.8} \times 10^{22} \text{ cm}^{-2}$ and covering factor = $0.64^{+0.11}_{-0.47}$. We also tried an ionized absorption model (*absori* in *xspec*) to fit the spectrum, and obtained $\Gamma = 1.47^{+0.38}_{-0.10}$, $N_H = 11.0^{+27.7}_{-4.2} \times 10^{22} \text{ cm}^{-2}$, the ionization

¹15.2'', 13.8'', 13.0'' respectively for PN, MOS1, MOS2

parameter² $\xi \sim 2200$. However, extra absorption (either partial covering absorption or warm absorber) is only statistically required at $\sim 97\%$ confidence level. For SDSS J081102+500724, more complex absorption does not give better fit to the spectrum.

3. Discussion

One of the four sources SDSS J153703+533219 was identified as high-ionization BAL (HiBAL), however, although Al III BAL trough is absent in this source, we can not rule out the possibility of low-ionization BAL (LoBAL) since Mg II is redshifted out of the spectroscopic coverage. The rest 3 sources are all LoBAL, specifically, SDSS J210757-062010 belongs to the rare class of iron LoBAL (FeLoBAL). This is consistent with the results from Ghosh & Punsly (2007) which found that most of the polar BAL QSOs are LoBAL.

Assuming that our BAL QSOs with polar outflows are intrinsically X-ray normal comparing with optically selected AGNs, we estimate their expected optical to X-ray index α_{ox} using eq. 6 in Strateva et al. (2005). We note that using the relation between radio and X-ray luminosities for radio loud quasars (Brinkmann et al. 2000) yields similar intrinsic α_{ox} for these BAL quasars. We can clearly see from Table 1 that the two detected sources have observed optical to X-ray index α_{ox} well consistent with expected ones, suggesting they are X-ray normal. We note the spectrum of SDSS J153703+533219 can be marginally better fitted (with a confidence level $\sim 97\%$) by a partial covering absorber or a warm absorber. Adopting the partial covering absorption model, we obtained an α_{ox} of 1.58 after absorption correction, and for the warm absorber model we obtained an α_{ox} of 1.67, both are still consistent with the expected value 1.69.

Both SDSS J145926+493136 and SDSS J210757-062010 are not detected with the XMM data. With the derived upper limits of the 2 – 10 keV fluxes, we obtained lower limits to their α_{ox} . We find that SDSS J145926+493136 is > 2 times fainter in 2 – 10 keV band than predicted based on α_{ox} estimation, while SDSS J210757-062010 is > 19 times fainter. Considering the scatter in the intrinsic α_{ox} of normal AGNs (~ 0.11 , Strateva et al. 2005), the X-ray weakness in SDSS J145926+493136 is statistically not robust (only at $> 1\sigma$ level), and for SDSS J210757-062010 the X-ray weakness is at $> 3.5\sigma$ level. Assuming a powerlaw spectrum ($\Gamma = 1.9$) with neutral intrinsic absorption, we estimate the lower limit to the neutral intrinsic absorption (see Table 1). Again, due to the large scatter in the α_{ox} estimation,

² $\xi = L/nR^2$, where L is the integrated incident luminosity between 5 eV and 300 keV, n is the density of the material and R is the distance of the material from the illuminating source (Done et al. 1992). During the fit, we assumed a temperature of 3×10^4 K and solar abundance for the absorber.

the lower limit to N_H for SDSS J145926+493136 suffers large uncertainty, and is statistically not robust.

In the popular theoretical model, the BAL outflow, initially launched from the accretion disk, is accelerated through radiation pressure (e.g. Murray et al. 1995). In this model strong X-ray absorption is required as a shield gas within the outflow, to prevent the UV outflow from being fully ionized. This is supported by the strong X-ray absorption detected in BAL QSOs. However, we find no evidence of strong X-ray absorption in two X-ray detected polar BAL QSOs. Considering the nature of polar outflows might be different from equatorial outflows, i.e., with different launch places, different acceleration mechanism (jet might play a major role in the acceleration of polar outflow), this result is not surprising. If this is true, the polar BAL might occur at larger distances than equatorial BAL, thus will not be fully ionized even without thick shielding gas. A consequence of this hypothesis is that the BAL line profiles might be different in polar outflows. Based on the small sample presented in Zhou et al. (2006), we can not tell the difference of line profile, line width, etc, if there is any. A much larger sample would be helpful to test this possibility by comparing with a well selected control sample. Meanwhile, as Ghosh & Punsly (2007) pointed out, an inordinately large fraction of polar BAL quasars are LoBAL, suggesting polar outflows are somehow physically different from equatorial outflows.

Meanwhile, the X-ray weakness in SDSS J210757-062010 which shows an X-ray weakness factor of > 19 suggests the existence of strong X-ray absorption. However, we note that SDSS J210757-062010 is an FeLoBAL. There are evidence showing that FeLoBAL might signify the transition between an ultraluminous infrared galaxy and quasar and does not arise due to a particular line of sight (e.g. Farrah et al. 2007). In this case, FeLoBAL might behave differently in X-ray, thus its nature does not represent that of polar BAL outflows. Note that except SDSS J210757-062010, all the rest three polar BAL quasars appear consistent with X-ray normal without strong absorption.

Finally, if strong X-ray absorber does exist in polar BAL quasars, there are several alternative explanations to the nondetection of X-ray absorption in two X-ray detected sources. First, it might be due to partial covering X-ray absorption, ionized absorber, or scattering component in the spectra, which were found normal in BAL QSOs (e.g. Green et al. 2001). In the spectrum of SDSS J153703+533219 we have found that a partial covering X-ray absorption or ionized absorption could marginally improve the spectral fitting at $\sim 97\%$ confidence level. For SDSS J081102+500724, however we are unable to confirm or rule out the existence of such complex absorption. Secondly, there might be significant contribution from the relativistic jets to the X-ray emission, which might originate at larger scale than the shielding gas, and thus be free from strong X-ray absorption. This is supported by

the very flat X-ray spectrum ($\Gamma = 1.31_{-0.09}^{+0.20}$) in SDSS J153703+533219, which is normal for radio loud AGNs (but not specifically by the spectrum of SDSS J081102+500724). This is further supported, though not conclusively, by the fact that the observed X-ray luminosities of the two detected sources are also consistent with the correlation between radio and X-ray luminosities for radio loud quasars (Brinkmann et al. 2000). Further studies are required to test above possibilities.

The work was supported by Chinese NSF through NSFC10773010, NSFC10533050 and the CAS "Bai Ren" project at University of Science and Technology of China.

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Table 1. XMM Observations of four polar BAL quasars

SDSS J	z	type ^b	Radio loudness	Date	good exp. ks	N_H 10^{22}cm^{-2}	Γ	$f_{2-10\text{keV}}$ $\text{erg}/\text{cm}^2/\text{s}$	C-stat/dof	α_{ox} obs.	α_{ox} exp.
153703+533219	2.4035	HiBAL?	31	2006-06-23	8.7	<0.44	$1.31^{+0.20}_{-0.09}$	1.0×10^{-13}	387/474	1.73	1.69
145926+493136 ^a	2.3700	LoBAL	29	2006-06-09	8.5	>4.1		$<1.4 \times 10^{-14}$		>1.77	1.66
081102+500724	1.8376	LoBAL	237	2007-04-18	10.0	<0.59	$1.71^{+0.30}_{-0.14}$	5.1×10^{-14}	289/369	1.55	1.60
210757-062010 ^a	0.6456	FeLoBAL	72	2007-04-24	6.3	>40		$<1.0 \times 10^{-14}$		>1.93	1.54

^aNot detected by the XMM exposures. Upper limits (1σ) to the 2 – 10 keV flux are given. The lower limits of absorption column density (N_H) are estimated by comparing the upper limits of X-ray count rates with expectations (see §3 for details).

^bClassified based on most updated SDSS spectrum. For SDSS J153703+533219, although Al III BAL trough is absent, we can not rule out the possibility of LoBAL since Mg II is redshifted out of the spectroscopic coverage.

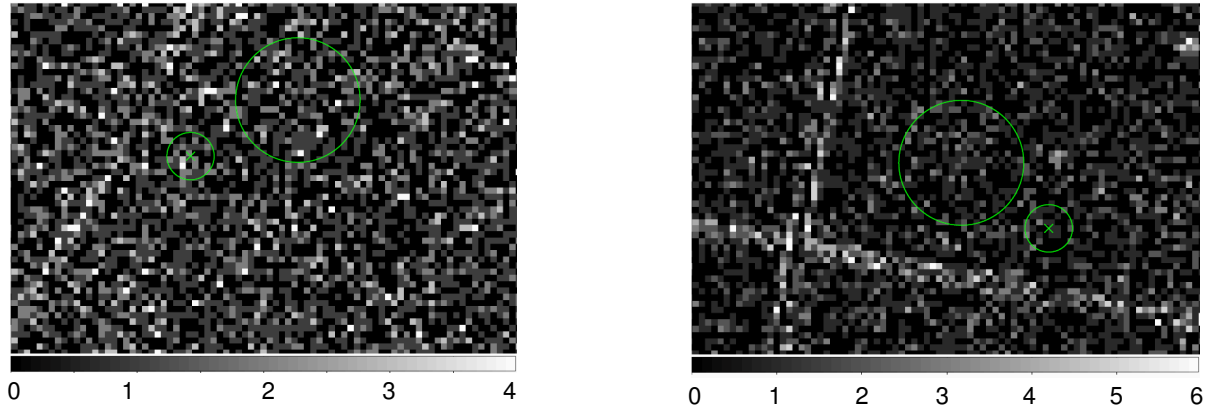


Fig. 1.— XMM PN 0.5 – 10 keV band images ($320'' \times 220''$) of SDSS J145926+493136 (left) and SDSS J210757-062010 (right). The expected positions of the sources (crosses) on the X-ray images, and circles used to extract source (small circles) and background counts (large circles) are marked.

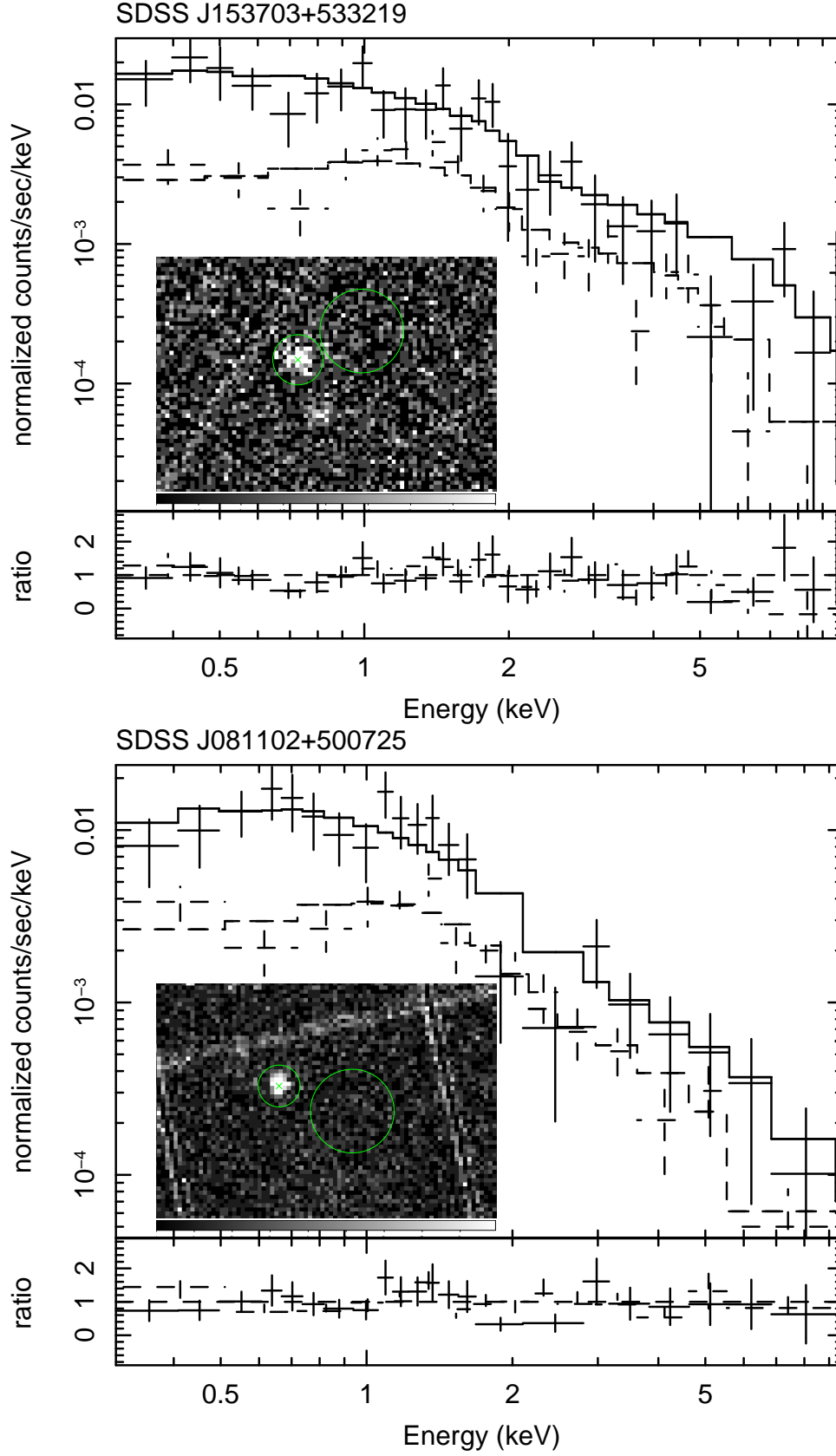


Fig. 2.— Spectral fitting (a powerlaw with neutral absorption) to the XMM PN (solid) and MOS (dotted) data of SDSS J153703+533219 and SDSS J145926+493136. The cutouts present the XMM PN 0.5 – 10 keV band images with source and background regions marked.